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Ultrasonic imaging of laboratory faults to illuminate the micro-mechanical origins of rate and state friction: Collaborative Research with Princeton University and The Pennsylvania State University

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Summary

A central problem in studies of fault mechanics and earthquake physics is that of quantifying frictional strength and developing constitutive laws that can be used to predict the dynamic and quasi-static properties of earthquake faults. Earthquakes are the culmination of a slip instability on natural faults. The weakening of the fault during the initial phase of accelerating slip is determined by the frictional properties of the sliding surface. In the absence of *in-situ* constraints on the physics of friction on natural faults, laboratory experiments have guided the design of relevant constitutive equations. Rate- and state-dependent friction is the most widely used representative of this class of friction theories. But despite several decades of experiments and significant progress in understanding some of the underlying processes that dictate fault friction, we have neither an adequate constitutive description, nor a complete mechanistic understanding, of rock friction at aseismic slip speeds.

The rate and state friction formulation requires a description of the time evolution of the 'state' variable, a proxy for the quantity and quality of real contact area on sliding interfaces and the porosity and particle characteristics in localized zones of shear within faults. However, the most widely used Aging (Dieterich) and Slip (Ruina) state evolution laws are both unable to explain the full range of laboratory experiments. Conventional wisdom has it that the results of velocity-step tests are best described by the symmetric response of the Slip law, while the logarithmic-with-time strengthening during slide-hold-slide tests is best described by the time-dependent healing of the Aging law. After reassessing the slide-hold-slide data we maintain that the evidence for time-dependent strengthening is in fact equivocal, while the evidence for slip-dependent strengthening following large velocity step decreases is unequivocal. Because both experiments probe the fault while it is well below steady state, we think that available evidence supports the view that fault healing in rock is fundamentally slip-dependent and not time-dependent.

Ultimately, our poor ability to characterize state evolution in laboratory faults stems from the difficulty of observing the processes that operate at the scale of micron-sized contact junctions and micron-sized particles within fault gouge. Recent advances in optical and ultrasonic monitoring of sliding surfaces hold out the promise of changing that. In fact, such experiments have already called into question the prevailing view that changes in state reflect primarily changes in contact area rather than contact quality or packing density within shear zones.

This proposal supported experiments to document the behavior of large velocity steps, long slide-hold-slides and normal stress-steps on bare rock and simulated gouge. The work was carried out at the Penn State Rock and Sedimentary Mechanics Lab. High resolution measurements of friction were complemented by ultrasonic monitoring of the sliding surface. The main novelties of our work involved data collected while the fault was far from steady state, which provides a more stringent test of proposed state evolution laws while being very relevant geologically. In addition, we monitored the fault using both transmitted P- and S-waves, which sheds additional light on the extent to which 'state' corresponds to contact area or quality.

This work was done collaboratively with Dr. A. Rubin and his team at Princeton University. Rubin's results from a previous NEHRP project suggested surprisingly different responses between the P- and S-wave transmissivity. The analytical, numerical, and parameter-inversion expertise of the Princeton group complements very well the relevant experimental and analytical expertise of the Penn State group. This synergy was leveraged strongly in the current project; it put us in a unique position to generate and analyze data from the lab experiments and to use them to describe rock friction in the context of the framework of the micro-mechanics of multicontact interfaces.

The Results of our work are expected to have significant impact on understanding fault mechanics and earthquake physics including triggering of seismic and aseismic fault slip and seismic hazard assessment.

Summary of Work Performed:

Laboratory Experiments

The experiments were performed in the Penn State Rock and Sediment Mechanics lab using the biaxial double-direct-shear configuration. For initially bare rock this configuration consists of one sliding block of Westerly granite sandwiched between 2 stationary blocks. For gouge it consists of two identical layers (2–6 mm in thickness) of either Westerly granite or quartz gouge sandwiched between three rigid forcing blocks. Shear is forced to occur within the gouge layer by coupling the edges strongly to the bounding surfaces by grooves oriented perpendicular to the shearing direction. For both rock and gouge the working distance (total slip) is 50 mm. Fast acting servo-hydraulic controllers are used to maintain specified boundary conditions (generally normal load and shear displacement rate). Mechanical data include shear stress, load point displacement, normal stress, and normal displacement perpendicular to the interface. We measure forces with strain gauge load cells, accurate to ±0.1 kPa and displacements with direct current displacement transducers, accurate to ±0.1μm. Stresses and displacements are recorded digitally at 10 kHz with a 24 bit system and averaged to 1–1000 Hz for storage.

The Penn State group performed the experiments, with help and input from the Princeton group and the Princeton group handled modeling and numerical studies that both informed improvements to the constitutive laws and guided additional experiments.

The work provided partial funding for Mr. P. Bhattacharya, a senior grad. student who finished his PhD at Princeton under the supervision of PI Rubin during the project. At Penn State Ms. K. Ryan and Mr. J. Leeman were supported. Mr. Leeman finished his PhD at Penn State under the supervision of PI Marone during the project. The Penn State team lead the effort on acoustic wave imaging. Leeman and Ryan had primary responsibility for the friction experiments and together with Marone optimized the loading control system to achieve large velocity steps and precise control on load point displacement and fault slip. Data analysis was carried out primarily at Penn State and also jointly, while the theoretical and numerical work were led by Mr.

Bhattacharya and Rubin.

Microscopic models of rate- and state-dependent friction; theory and numerical simulations

It has been known for decades that laboratory velocity step experiments are well-modeled by the "Slip" law for state evolution. For both the experiments and the Slip law, following the velocity step the stress approaches the new steady-state value exponentially with slip, over a slip distance that is independent of the size or sign of the velocity step. The behavior following the velocity step decreases in particular is incompatible with the "Aging" law for state evolution, which predicts that the surface heals with the logarithm of time even for arbitrarily low slip speeds, and therefore that the surface strengthens over smaller and smaller slip distances as the velocity step decrease becomes increasingly large. However, even though a clear physical picture has been proposed to explain the Aging evolution law ("mushrooming" of contact points with the logarithm of time under high local stresses), a comparable physical justification for the Slip law has been lacking. In addition, although the Slip law does an excellent job of matching velocity step experiments, no proposed state evolution law does a good job of fitting both velocity-step and slide-hold-slide experiments. This suggests, as observed by Ruina [1983], that it might be necessary to search for state evolution laws beyond the simple form where the derivative of state with respect to time depends only on the current values of velocity and state, and not on (e.g.) a more complex function of prior sliding history.

The response to velocity step decreases suggests that approaching the new steady state frictional strength requires swapping out the old contacts and swapping in the new, regardless of how much time that takes. One physical picture consistent with this conclusion is that individual asperities have a heterogeneous strength, with each portion "remembering" the conditions at which it became part of the asperity. Graduate student Tianyi Li (Princeton) is exploring one such mechanism, where the intrinsic strength depends logarithmically on the velocity at which the local portion of a contact was slid into existence, and remains unchanged thereafter. Such a mechanism could be consistent with the diffusion of impurities either into or out of the contact, if this diffusion is much more efficient at the margins of the contact than within the contact interior, and if impurity concentration defines state. This numerical approach also requires assuming an asperity size distribution; we assume square asperities with an exponential distribution of side lengths with a characteristic scale D_c. For our initial simulations we assume that the two asperities forming a single contact are of the same size and are perfectly aligned in the slip-perpendicular direction. The numerical scheme then keeps track of the state of individual grid elements as they enter, slide along, and exit the contact. The grid spacing $\Delta\delta$ is of order $D_c/20$. The smallest asperity has side length $\Delta\delta$, and the largest is roughly $10D_c$. These values are respectively small and large enough that they do not affect the numerical results.

For this model we have found an analytical solution for friction as a function of slip distance following a perfect velocity step on the sliding surface. This solution is very similar to that for the Slip law, deviating from it only by a slowly-changing factor in front of the exponential decay to the future steady state value. Given this, we were able to produce numerical fits to the large-velocity-step data of *Bhattacharya et al*. [2015], carried out on synthetic fault gouge in the Penn State lab, that were as good as the classical Slip law fits (Figure 1). We then turned to the slide-hold-slide data of *Beeler et al*. [1994], since their use of two different machine stiffnesses is useful for distinguishing between slip-dependent and time-dependent fault healing. Neither the Slip nor the Aging law fits these data well [Bhattacharya, P., A.M. Rubin, and N.M. Beeler, 2017, "Is fault healing in rock friction experiments really time dependent?" submitted to *J. Geophys.*

Res. Solid Earth]. Our hope was that because our new scheme is not identical to the Sip law, it could do a better job fitting the slide-hold-slide data; unfortunately, this is not the case. It appears that this new law is too close to the Slip law to do so.

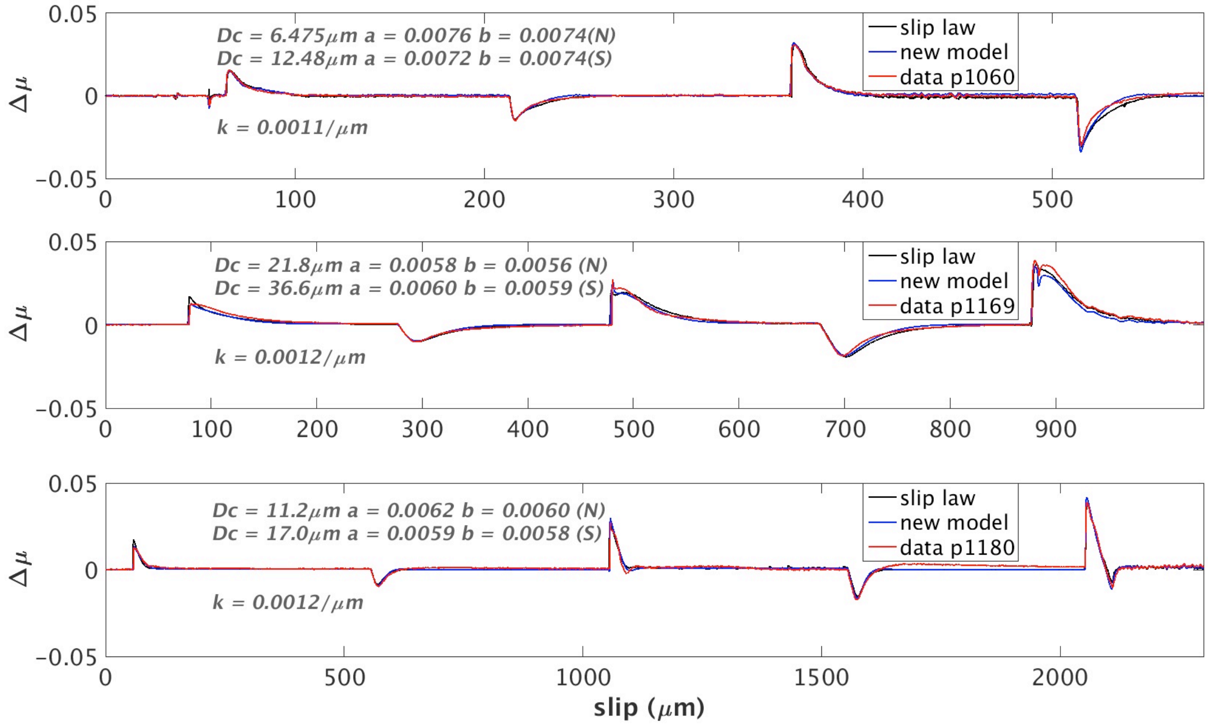

Figure 1: Inversion results for data p1060, p1169 and p1180, comparing the best fit of the Slip-law-like model with the best fit of the Slip law (data from *Bhattacharya et al.* [2015]). The new model shows a slightly better performance for perturbations around some step-ups. Numerical parameters: p1060: $D_{max}/Dc = 9.2$, $D_c/\Delta\delta = 25$; p1169: $D_{max}/D_c = 7.3$, $D_c/\Delta\delta = 44$; p1180: $D_{max}/D_c = 7.2$, $D_c/\Delta\delta = 28$. These ratios are large enough to not affect the numerical results.

Given that our proposed law did not remedy all the shortcomings of the existing Aging and Slip laws, we next tailored our model to evaluate the concepts underlying the Aging evolution law. This law is written $d\theta/dt = 1 - V\theta/D_c$, where t is time, θ is state, V is slip speed, and D_c is the characteristic sliding distance for the evolution of θ. Traditionally, θ has been equated with contact age. This view is easily rationalized for long stationary holds (V=0 so $d\theta/dt$=1), and for steady-state sliding ($d\theta/dt = 0$, so $\theta = D_c/V$, where D_c is now interpreted as a characteristic asperity dimension). However, it is not clear that state as given by the Aging law corresponds in any way to contact age when $V\theta/D_c >> 1$ (where as an aside the Aging law is known to fail to reproduce laboratory friction experiments). Physical interpretations of the Aging law focus on stationary contacts, where it can be argued that contact area grows logarithmically with time [e.g., *Baumberger and Caroli*, 2006], and hence it makes sense that strength would increase logarithmically with contact age (state).

We can easily modify our numerical algorithm to track the time that individual grid elements have been part of a contact, rather than the velocity at which they entered the contact. Different results are obtained depending upon whether and how one averages the element ages before taking their logarithm. Interestingly, we obtain a solution very similar to the Aging law when we adopt what we believe to be a nonphysical definition of "age"; that is, when we take the logarithm of the average contact time on the surface. We regard this as nonphysical in that the strength of each contact depends upon the history of all its neighbors rather than its own history. Of the approaches that seem more physically justifiable, whether we take the logarithm of the contact time of each grid element separately and then sum them, or average the contact time of all the grid elements within each asperity before taking their logarithm, we obtain results that are very similar to the classical Aging law for velocity step decreases, where contacts heal with time, but that are much more similar to the Slip law following velocity step increases, where the surface is weakening primarily because old contacts are being destroyed and new ones formed (Figure 2). While we are not advocating this as a new evolution law, it does remove one glaring deficiency of the Aging law (that being linear slip-weakening behavior when $V\theta/D_c >> 1$, at a rate that is independent of $V\theta/D_c$), and it also clarifies the point that under the Aging law state is not synonymous with contact age under general slip histories. This work is described in a paper currently in review [Li, T., and A.M. Rubin, 2017, A microscopic model of rate and state friction evolution, submitted to *J. Geophys. Res. Solid Earth*]

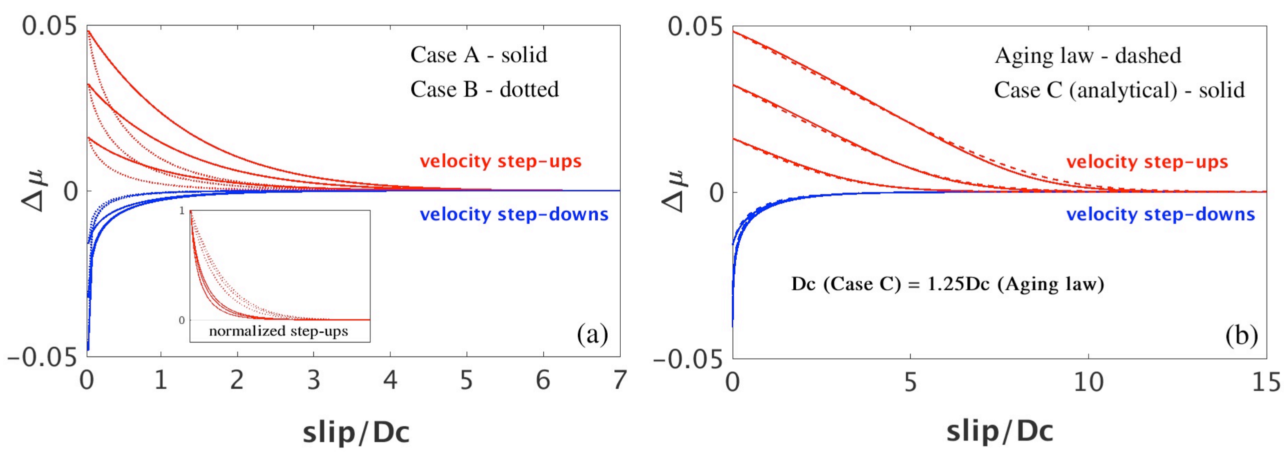

Figure 2: Three Aging-law-like models that differ in whether or how the individual grid element ages are averaged before taking their logarithm . Left: Cases A (no averaging) and B (ages are averaged on an asperity-by-asperity basis). Numerical results; $D_c/\Delta\delta = 7$; $D_{max}/Dc = 25$. Right: Case C (the entire surface is averaged before taking the logarithm; analytical result) compared to the classical Aging law. Note that in both Case A and B, the slope of the friction curve is not initially the same for velocity step-ups of different magnitudes, consistent with experiments. Inset: normalized velocity step increases for Cases A & B. Larger velocity steps have slightly larger slip-weakening distances.

Technique

Experiments were conducted using a servo-controlled, biaxial apparatus with a double-direct shear configuration. The samples were loaded in shear displacement servo-feedback with 0.1 μm resolution to achieve a constant displacement rate of a load point at the top of the center block of the double-direct shear assembly. The load point displacement history consisted of a series of linear functions with steps imposed to mimic changes a tectonic loading velocity. Shear occurred at constant normal stress, or with imposed changes in normal stress, which was was implemented with a servo-controlled load-feedback mechanism (with 0.1 kN resolution). The stiffness of the vertical loadframe is 5 MN/cm or 250 MPa/cm when expressed as the shear stress on a sample with nominal friction contact dimensions of 10 cm x 10 cm. Stiffness of the apparatus and sample assembly is 0.017 MPa/μm, as determined in-situ by measuring the instantaneous shear stress response to a step change in loading rate.

The positions of both rams were measured by displacement transducers (DCDTs) throughout each experiment. Using the position of the vertical ram and correcting for the stiffness of the loading apparatus allowed us to determine shear displacement at the gouge layer boundaries and shear strain within the layer. The amount of inelastic slip (creep) preceding instability and the dynamic slip was recorded at each instability. Recording the displacement of the horizontal ram throughout the experiment allowed for reconstruction of the change in gouge thickness both over the course of the entire experiment due to geometric thinning, as well as for dilation and compaction of the sample during the stick-slip cycle.

Samples were pre-conditioned at a constant shear velocity for approximately 1 mm of displacement until a steady-state maximum shear stress was reached. After achieving steady state conditions, the computer controlled displacement and velocity history was imposed.

Publications resulting from this award.

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3. Dorostkar, O., Guyer, R. A., Johnson, P. A., Marone, C. and J. Carmeliet, On the role of fluids in stick-slip dynamics of saturated granular fault gouge using a coupled computational fluid dynamics-discrete element approach, in press, *J. Geophys. Res. Solid Earth,*, 2017.

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11. Scuderi, M. M., Viti, C., Tinti, E., Collettini, C. and C. Marone, Evolution of Shear Fabric in Granular Fault Gouge From Stable Sliding to Stick-Slip and Implications for Fault Slip Mode, in Press, *Geology*, 2017.

12. Tinti, E., Scuderi, M. M., Scognamiglio, L. Di Stefano, G., Marone, C., and C. Collettini, On the evolution of elastic properties during laboratory stick-slip experiments spanning the transition from slow slip to dynamic rupture, *J. Geophys. Res. Solid Earth*, 10.1002/2016JB013545, 2016.

13. Wojatschke, J., Scuderi, M. M., Warr, L. N., Carpenter, B. M., Saffer, D., and C. Marone, Experimental constraints on the relationship between clay abundance, clay fabric and frictional behavior for the Central Deforming Zone of the San Andreas Fault, *Geochem. Geophys. Geosyst.*, 10.1002/2016GC006500, 2016.

The following web site contains information relevant to work completed for this proposal: http://www.geocs.psu.edu/~cjm/